

# NEUTRINO OSCILLATION EXPERIMENTS AT NUCLEAR REACTORS

GIORGIO GRATTA

*Physics Department, Stanford University, Stanford, CA 94305, USA*

*E-mail: [gratta@hep.stanford.edu](mailto:gratta@hep.stanford.edu)*

In this paper I give an overview of the status of neutrino oscillation experiments performed using nuclear reactors as sources of neutrinos. I review the present generation of experiments (Chooz and Palo Verde) with baselines of about 1 km as well as the next generation that will search for oscillations with a baseline of about 100 km. While the present detectors provide essential input towards the understanding of the atmospheric neutrino anomaly, in the future, the KamLAND reactor experiment represents our best opportunity to study very small mass neutrino mixing in laboratory conditions. In addition KamLAND with its very large fiducial mass and low energy threshold, will also be sensitive to a broad range of different physics.

## 1 Introduction

Neutrino oscillations, if discovered, would shed light on some of the most essential issues of modern particle physics ranging from a better understanding of lepton masses to the exploration of new physics beyond the Standard Model. In addition finite neutrino masses would have important consequences in astrophysics and cosmology.

Experiments performed using both particle accelerators and nuclear reactors have been carried-on extensively in the past 20 years finding no firm evidence for neutrino oscillations. However, in recent years, evidence has been collected on a number of effects that could point to oscillations: the solar neutrino puzzle, the anomaly observed in atmospheric neutrinos<sup>1</sup> and the LSND effect<sup>2</sup>. This paper will concentrate on the first two cases that are well suited to be studied with reactor experiments. Both effects, if interpreted as signals for neutrino oscillations, would suggest very small neutrino mass differences and, possibly, large mixing parameters. We write the probability of oscillation from a flavor  $\ell$  to another one  $\ell'$  as

$$P_{\ell\ell'} = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu} \quad (1)$$

where  $L$  is expressed in meters,  $\Delta m^2$  in  $\text{eV}^2$  and  $E_\nu$  in MeV. It is clear that in order to probe sufficiently small  $\Delta m^2$ , long baselines have to be combined with low energy neutrinos. Unfortunately we are able to collimate neutrino beams only by using the Lorentz boost of the parent particles from which decay the

neutrinos are produced. For this reason low energy neutrinos are generally produced over large solid angles while high energy ones may come in relatively narrow beams. Hence to access, for instance, the atmospheric neutrino  $\Delta m^2$  region we have the choice of either using the beam from an accelerator that is rather narrow (better than  $\approx 1$  mrad) but has an energy of several GeV, or detecting few-MeV neutrinos emitted isotropically by a nuclear reactor. In the first case the baseline will have to be much larger, but since the beam is pointing, both cases turn out to be quite feasible and their different features make them quite complementary. As reactors produce exclusively electron anti-neutrinos, only  $\bar{\nu}_e - \bar{\nu}_X$  oscillations can be observed. In addition since the neutrino energy is below the threshold for producing muons (or  $\tau$ s), reactor experiments have to be of “disappearance” type, that is oscillation would be detected as a deficit of electron neutrinos. This feature, together with the higher energies produced in accelerator neutrino events and their time-bunched structure, makes accelerators-based experiments more immune to backgrounds and, in general, more sensitive to small mixing parameters. On the other hand the very low energy of reactor neutrinos offer the best chance to push to the limit our exploration of the small  $\Delta m^2$  regime.

Two reactor-based experiments have been performed to study the parameter region consistent with atmospheric neutrinos extending our reach in  $\Delta m^2$  by over an order of magnitude. While the Chooz<sup>3</sup> experiment has been completed (although part of the data is still being analyzed), Palo Verde<sup>4</sup> is taking data since the fall 1998 and will continue at least until the end of 1999. KamLAND<sup>5</sup> will be the first laboratory-style experiment able to attack one of the regions of solar neutrino oscillations.

## 2 Reactors as Neutrino Sources

Nuclear reactors produce isotropically  $\bar{\nu}_e$  in the  $\beta$  decay of the neutron-rich fission fragments. For all practical purposes the neutrino flux and spectrum depend only on the composition of the core in terms of the four isotopes  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$  being fissioned in the reactor. Neutrinos are then produced by long chains of daughter isotopes and hundreds of different  $\beta$ -decays have to be included to account for the observed yields. The modeling of such processes is quite a formidable task but there is nowadays a very good agreement between theoretical calculations and experimental data. Two methods can be used to experimentally cross check theoretical models. In one case the electron spectra for fission-produced chains can be experimentally measured for each of the four parent isotopes. From this data, available only for ( $^{235}\text{U}$ ,  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$ ), anti-neutrino spectra can be derived without loss of

accuracy<sup>6</sup>, obtaining a total uncertainty on the flux of about 3%. Alternatively anti-neutrino flux and spectra have been directly measured<sup>7</sup> in several high statistic experiments with detectors of known efficiency. These data are usually a by-product of previous reactor oscillation experiments where the anti-neutrino have been measured at different distances. Since these observations have been found to be consistent with a  $1/r^2$  law (no oscillations at short baselines) they can now be used as a determination of the absolute anti-neutrino spectra. A total error of about 1.4% has been achieved in these measurements.

All measurements and calculations agree with each other within errors so that, given the history of power and fuel composition for a reactor, its anti-neutrino energy spectrum can be computed with an error of about 3%. We note here that for this kind of experiments a “near measurement” is superfluous as, in essence, all the information needed can be readily derived from the previous generation of experiments, using their result that no oscillations take place at those shorter baselines. The real challenges consist in measuring precisely the detector efficiency and in subtracting backgrounds properly.

Since the neutrino spectrum is only measured above some energy threshold ( $M_n - M_p + m_e = 1.8$  MeV), only fast (energetic) decays contribute to the useful flux and the “neutrino luminosity” tracks very well in time the power output of the reactor. Generally few hours after a reactor turns off the neutrino flux above threshold has become negligible. Similarly, the equilibrium for neutrinos above threshold is established already several hours after the reactor is turned on.

While early oscillation experiments used military or research reactors, modern experiments have long baselines and so need the largest available fluxes (powers) that are usually available at large commercial power generating stations. Typical modern reactors have thermal power in excess of 3 GW ( $> 1$  GW electrical power) corresponding to  $\simeq 7.7 \times 10^{20} \nu/s$ . Usually more than one such reactors are located next to each other in a power plant so that the neutrino flux detected is the sum of the contributions from each core. Although periods of time with source off would be very useful to study the backgrounds, in the case of multiple reactors, plant optimization requires the refueling of one reactor at the time so that in practice backgrounds are often studied at partial power (instead of zero power). Typically each reactor is off (refueling) for about one month every one or two years. A notable exception is Chooz where the experiment was running before the power plant was operational. This experiment was then able to record the slow turn on of the reactors during commissioning as shown in Figure 1. This is used to cross check other estimates of the backgrounds to the measurement. KamLAND

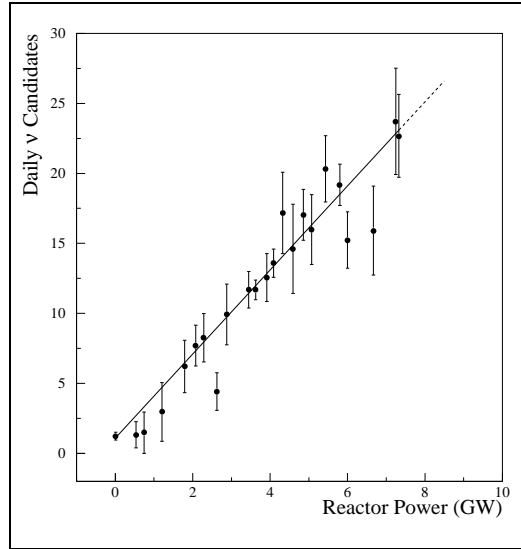


Figure 1. Neutrino candidates in the Chooz detector as function of the thermal power in GW.

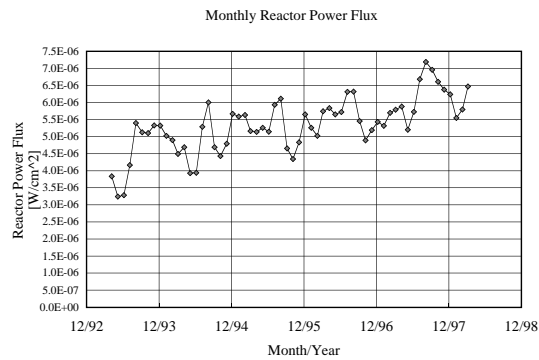


Figure 2. Time-modulation of the anti-neutrino flux from reactors at Kamioka. The coherent decrease of flux in the spring and fall is due to reactor refueling and maintenance performed when electricity demand is at minimum.

will detect neutrinos from a very large number of reactors in several power plants distributed in the central region of Japan. In this case an important

check of backgrounds will result from the study of a 6-month period modulation in the neutrino flux due to concentrated reactor refuelings and maintenance in the fall and spring periods, when electricity demand is lowest. Such a modulation, with a strength of about 30% of the full flux, is illustrated in Figure 2.

### 3 Oscillation Searches in the Atmospheric Neutrino Region

At the time of writing two experiments are exploring the region of phase-space with  $10^{-3} < \Delta m^2 < 10^{-2}$ : Chooz in France (a 2-reactor site) and Palo Verde in the United States (a 3-reactor site). In order to be sensitive to oscillations in the atmospheric neutrino region the Chooz and Palo Verde detectors are located, respectively,  $\simeq 1$  km and  $\simeq 0.8$  km from the reactors. In both cases the detection is based on the inverse- $\beta$  reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (2)$$

in Gadolinium-loaded liquid scintillator. The detectors can measure the positron energy so that the anti-neutrino spectrum can be easily reconstructed from simple kinematics as

$$E_{\bar{\nu}} = E_{e^+} + (M_n - M_p + m_e) + \mathcal{O}(E_{\bar{\nu}}/M_n). \quad (3)$$

Given a fixed baseline, different energies have different oscillation probabilities and, for a large range of  $\Delta m^2$  values, the signature of oscillations is an unmistakable distortion of the energy spectrum. The slight difference in baselines for the two experiments could result in rather different oscillation signals, providing a nice cross-check against non-oscillation effects. Parameter sets closer to the sensitivity boundaries will ultimately give neutrino spectra similar to the case of no oscillations, so that to reach the best sensitivity both experiments will have to rely on the absolute neutrino flux measurement. Since at these large distances from the reactors the flux of neutrinos is rather low, special precautions have to be taken in order to suppress backgrounds from cosmic radiation and natural radioactivity. Although both detectors are located underground, background rejection is achieved somewhat differently in the two cases. On one hand Chooz has been built in a rather deep (300 m.w.e.) already existing underground site, while, on the other, Palo Verde was installed in a shallow laboratory (32 m.w.e.) excavated on purpose. Hence this last experiment is segmented and uses tighter signatures to identify anti-neutrino events.

The central detector of Palo Verde, a matrix of 66 acrylic cells each 9 m long, is surrounded by a 1 m thick water buffer that shields  $\gamma$  radiation and

neutrons. A large veto counter encloses the entire detector, rejecting cosmic-ray muons. In this detector the signal consists of a fast triple coincidence followed by the neutron capture. The triple is produced by the ionization due to the positron and, in two different cells, its two annihilation photons. Timing information at the two ends of each cell allows to reconstruct the events longitudinally and to correct for light attenuation in the cells, providing a good quality positron energy measurement.

The Chooz detector, on the other hand, being in a lower background environment, is a single spherical acrylic vessel filled with liquid scintillator. It triggers on the double coincidence between the positron and the neutron parts of the inverse  $\beta$  reactions. Also in this case the central detector is surrounded by a veto and some shielding layers.

Gadolinium doping of the scintillator reduces the neutron capture time and hence the background. A concentration of 0.1% Gd by weight reduces the capture time from  $170\mu\text{s}$  to  $28\mu\text{s}$ . Since a neutron capture in Gd is accompanied by a 8 MeV photon cascade, another advantage of the doped scintillator is that it allows for a very high threshold for the neutron part of the event. This threshold, well above the Th and U lines, results in further reduction of the background.

Although both detectors are built using low activity materials, this requirement is more severe for Chooz in order to have a  $\gamma$ -ray rate consistent with the lower cosmic-ray induced background.

Two categories of backgrounds are considered: one is given by random hits in the detector (2 for Chooz, 4 for Palo Verde) produced by independent  $\gamma$ -rays and/or neutrons, while the other is given by single or double fast neutrons produced outside the veto by cosmic-ray muons mainly in spallation processes. Neutrons can deposit some energy simulating the fast part of the event and then thermalize and capture in Gd (like the neutrons from the anti-neutrino capture process). Unlike the case of independent hits, in this second background the event has the same time-structure of real events, so that its rejections is a-priori more difficult. The expected rates of neutrino events for the case of no oscillations is about  $30\text{ day}^{-1}$  for both detectors. Both groups use rather advanced trigger and data acquisition systems to select and log neutrino events.

At the present time both experiments see fluxes that are completely compatible with the expectations for no oscillations. From these observations the reactor experiments can exclude that oscillations involving electron neutrinos are causing the atmospheric neutrino anomaly. This result is quantitatively illustrated in Figure 3 <sup>8</sup>.

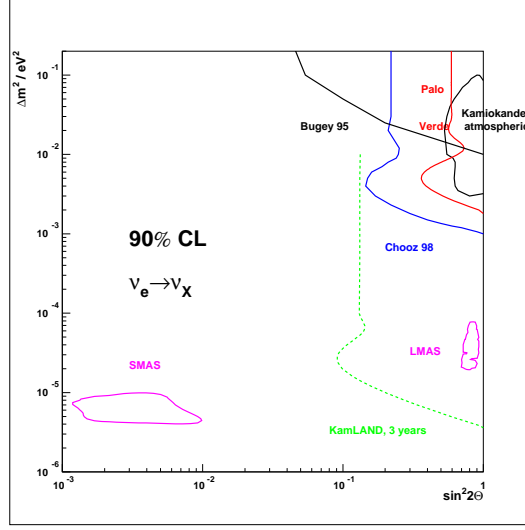


Figure 3. Phasespace for  $\nu_e - \nu_\mu$  oscillations in the region relevant for modern reactor experiments. The 90% CL limits from Chooz and Palo Verde are shown together with the KamLAND projected sensitivity assuming 3 years of data-taking and no evidence for oscillations. The Palo Verde result includes only the first 70 days of data in 1998. The MSW mechanism is used in plotting the solar neutrino regions. The sensitivity of reactor experiments is the same for  $\nu_e - \nu_\tau$  oscillations.

#### 4 Physics with KamLAND

The KamLAND experiment will use the Kamiokande infrastructure, under 1000 m rock overburden, to perform an ultra-long baseline experiment with enough sensitivity to test the large mixing angle MSW solution of the solar neutrino puzzle. KamLAND, will consist of 1000 tons of liquid scintillator surrounded by 2.5 m thick mineral oil shielding layer. Both liquids are contained in a 18 m diameter stainless-steel sphere that also supports, on the inside surface, about 2000 17-inch photomultipliers giving a 30% photocathode coverage. Such photomultipliers are modified from the 20-inch SuperKamiokande tubes and provide 3 ns FWHM transit-time-spread, allowing 1 MeV energy depositions to be localized with 10 cm accuracy. The detector light yield will be better than 100 p.e./MeV. A veto detector will be provided by flooding with water the volume outside the sphere and reading the Čerenkov light with old Kamiokande photomultipliers. A schematic view of the detector is shown

in Figure 4. In Table 1 we list the power, distance and neutrino rates for the

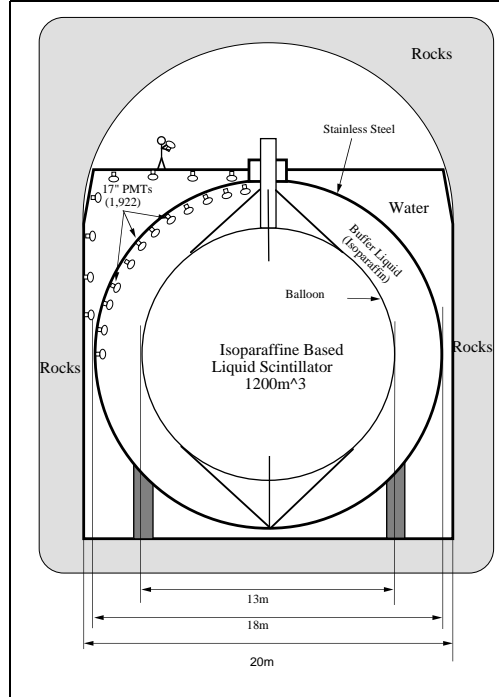


Figure 4. Schematic view of the KamLAND detector.

five nuclear plants giving the largest  $\bar{\nu}_e$  flux contributions together with the total from all Japanese reactors ( $\sim 2$  events  $\text{day}^{-1}$ ).

Extensive detector simulations predict that the main backgrounds will result from random coincidence of hits from natural radioactivity (0.05 events/day) and neutrons produced by muon spallation in rock (0.05 events/day). Hence the signal/noise ratio for reactor anti-neutrinos is expected to be about 20/1. While the predicted exclusion contour for the case of 3-years of data taking and no evidence of oscillations is shown in Figure 3, Figure 5 shows the precision to which the two oscillation parameters would be measured in 3 years if oscillations would indeed occur according to the large mixing angle MSW solution of the solar neutrino puzzle. In addition to the neutrino oscillation physics described above KamLAND will also perform a number of new measurements in the fields of terrestrial neutrinos, supernovae



Reactor Site	Number of Reactors	Thermal Power (GW)	Distance (km)	Rate (Events/year)
Kashiwazaki	7	24.6	160	348
Ohi	4	13.7	180	154
Takahama	4	10.2	191	102
Hamaoka	4	10.6	214	84
Tsuruga	2	4.5	139	84
Total	51	130		1075

Table 1. Expected contribution of different reactors to the neutrino rates to be detected in KamLAND in the case of no oscillations. Several other reactors each giving a small contribution do not have individual entries in the table but are included in the total. While the rates in the table are referred to the nominal power of the reactors the typical running duty cycle is 80%.

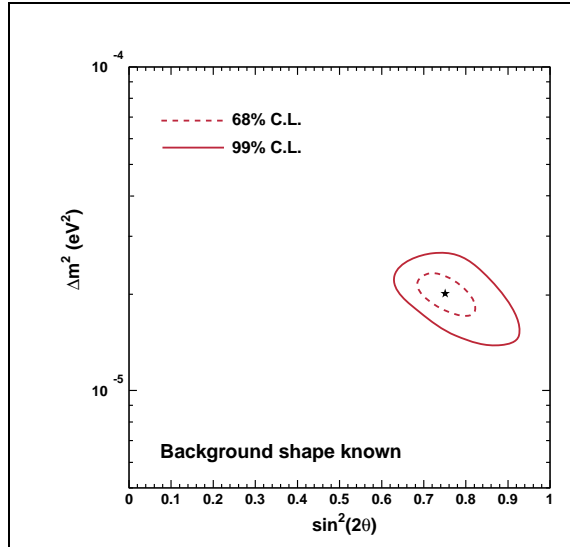


Figure 5. Error contours expected at 68% and 99% CL. The plot assumes 3 years of KamLAND reactor data and oscillations at  $\sin^2 2\theta = 0.75$ ,  $\Delta m^2 = 2 \times 10^{-5}$ . In the analysis the shape of the background in energy was assumed known but the integral was left as free parameter in a fit to power excursions of the type shown in Figure 2.

physics and solar neutrinos.

Construction for KamLAND has started in 1998 and data taking is scheduled to begin during 2001.

In conclusion it appears that the study of reactor neutrinos is a very interesting field indeed, offering the opportunity of exciting measurements and discoveries. The next 5 to 10 years should be rich of results !

## 5 Acknowledgments

I would like to express my gratitude to my collaborators in the Palo Verde and KamLAND experiments for lots of interesting discussions on neutrino physics. I am also indebted with C. Bemporad who provided me with the material about the Chooz experiment.

## References

1. Y. Suzuki, these proceedings.
2. H. White, these proceedings.
3. H. de Kerret *et al.* "Chooz Proposal", 1993, Unpublished.
4. F. Boehm *et al.* "Proposal for the San Onofre Neutrino Oscillation Experiment", Caltech 1994, Unpublished; updated by F. Böhm *et al.* "Addendum to the San Onofre Proposal" Calt-63-721 (1996), Unpublished.
5. P. Alivisatos *et al.* "KamLAND a Liquid scintillator Anti-Neutrino Detector at the Kamioka site", Stanford-HEP-98-03, Tohoku-RCNS-98-15, July 1998 (Unpublished).
6. K. Schreckenbach *et al.*, Phys. Lett. B99 (1981) 251; B160 (1985) 325; F. von Feilitzsch *et al.*, Phys. Lett. B118 (1982) 162; A. A. Hahn *et al.*, Phys. Lett. B218 (1989) 365.
7. B. Achkar *et al.*, Nucl. Phys. B434 (1995) 503; Y. Declais *et al.*, Phys. Lett. B338 (1995) 383; G. Zacek *et al.*, Phys. Rev. D34 (1986) 2621.
8. M. Apollonio *et al.*, Phys. Lett. B420 (1998) 397.